Final Lithium Experiments on CDX-U and LTX Status

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Outline

CDX-U

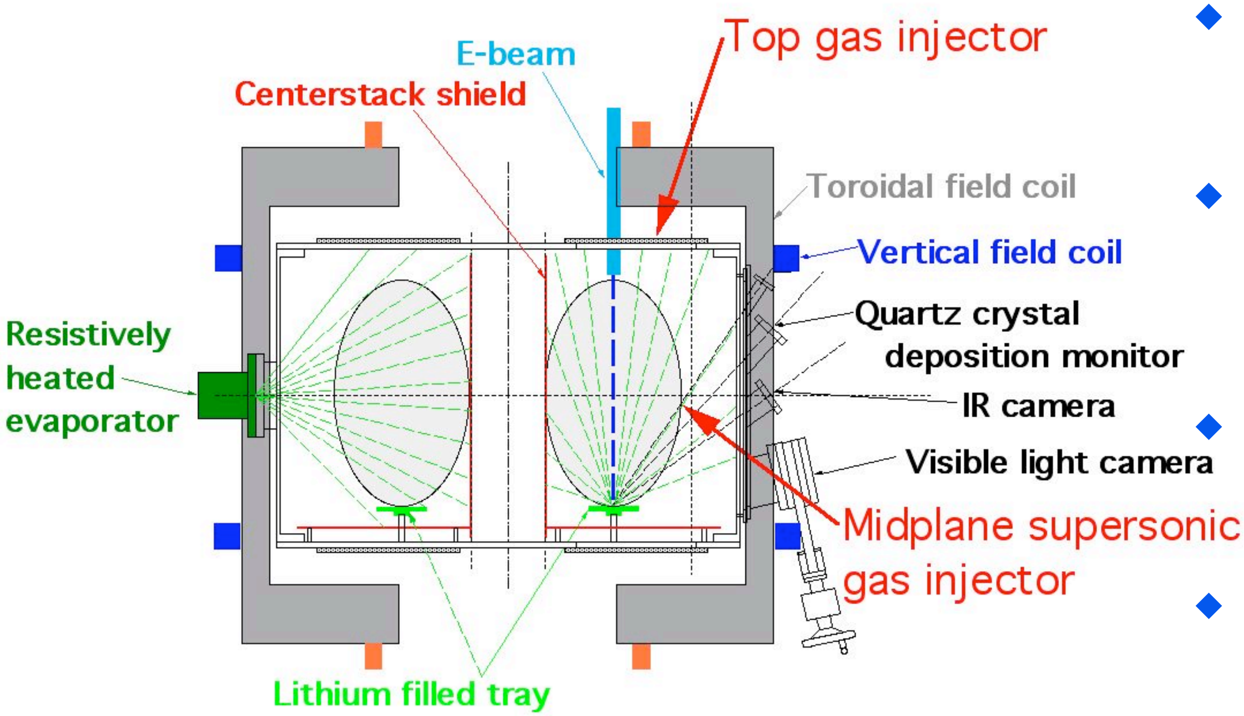
- CDX-U lithium and fueling systems for 2005
- Electron beam evaporation system
  - Enables deposition of 1000Å wall coatings in < 5 min.
  - Liquid lithium has very high power density capabilities
- Particle confinement time and recycling
  - ~30% recycling coefficient (record for magnetically confined plasmas)
- New magnetics, equilibrium reconstruction
- Plasma confinement
  - Up to an order of magnitude increase in confinement times
  - Exceeds ITER98P(y,1) scaling by 2 - 4×
    - » Record confinement enhancement for an ohmic tokamak
- LTX status
- Where is this headed?

Three lithium, two gas fueling systems available

CDX-U LTX

CDX-U:

R_0=34 cm	κ≤1.6	$I_P \le 80$ kA	$T_e(0)$~100 eV
a = 22 cm	$B_T(0)$2.2 kG	τ_{disch}<25 msec	$n_e(0)<6\times10^{19}$ m^{-3}



R_0= 34 cm, width = 10 cm
6 mm deep

- Lithium tray limiter
  - 300 g of lithium in a toroidal tray
- Electron beam high heat flux, lithium coating system
  - Used lithium tray inventory as source
- Resistively heated lithium evaporator
  - NSTX prototype
- Gas injection systems
  - Wall mounted piezo valve
  - Supersonic gas injector

⇒Up to 1000Å of lithium coatings between discharges

⇒600 cm² of liquid lithium forms lower limiter

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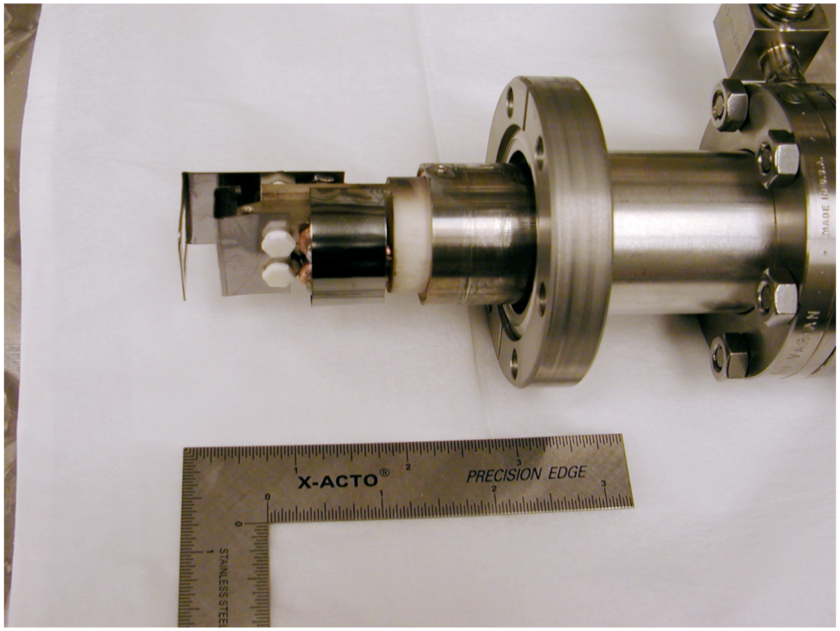
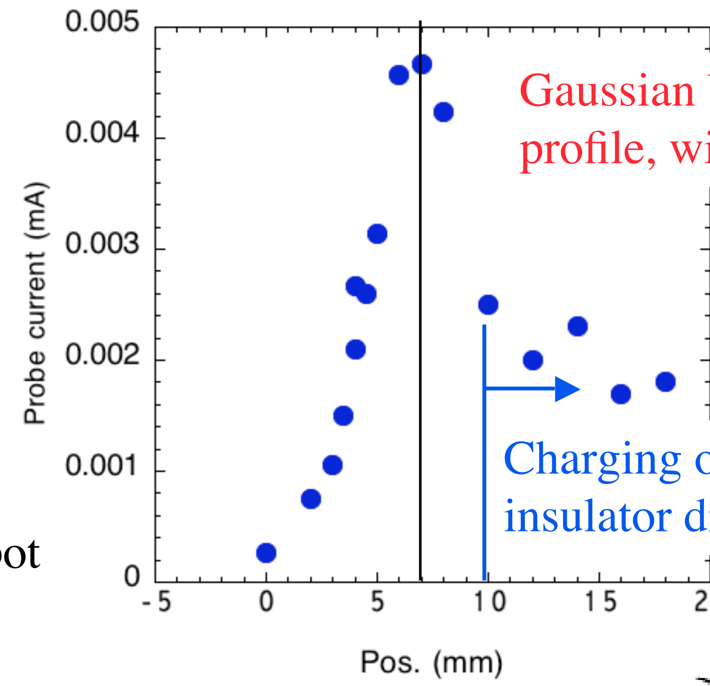
High power density electron gun intended to “spot heat” lithium

CDX-U



- Converted commercial gun
- 4 kV, 300 - 400 mA typ.
- 300 - 400 sec. run typical
- Uncooled (Tantalum, Macor, SS)
- Total power modest: <1.6 kW
- Power density high: < 60 MW/m^2



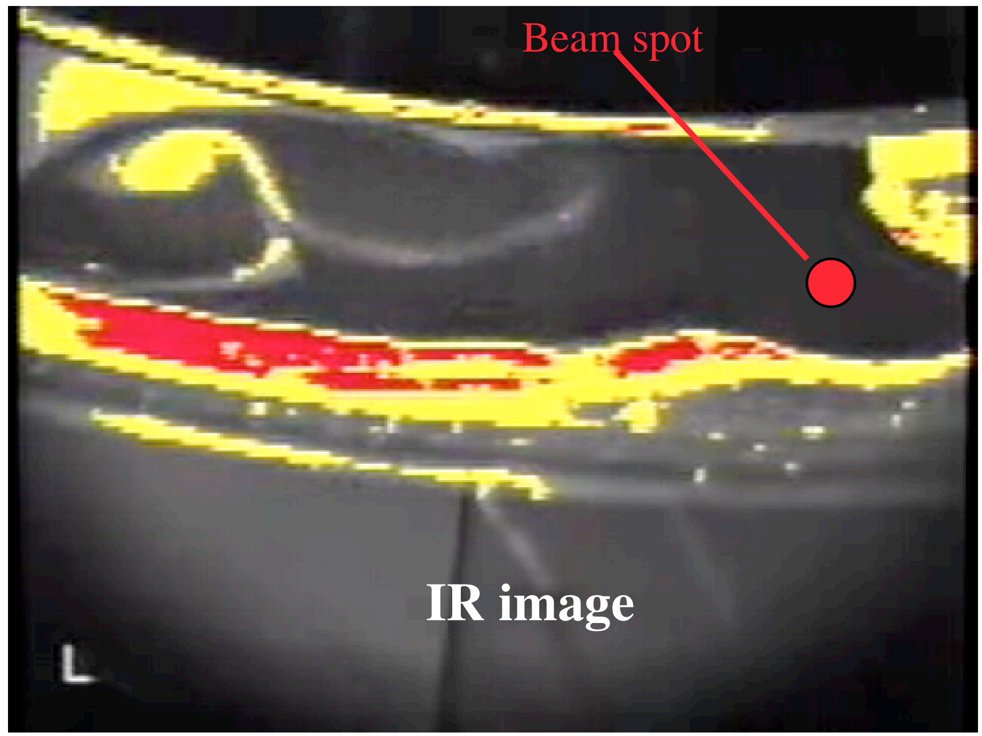
- Objective: 1000Å lithium wall coatings
  - TF + VF used to guide beam
    - » Can be pulsed to 600G; typ. 200 G
  - Lithium tray fill (~3 mm deep)used as evaporation target.
    - » Lithium area ~600 cm^2 >> beam spot
- **Spot heating proved impossible**

⇒Electron beam heating induces flow
⇒Flow very effectively inhibits localized heating

CDX-U

- IR camera movie of 25 sec. of a 300 sec. beam run
- Yellow denotes +55°C, red denotes +110°C
- Field ramps from 200 G to 400G 10 sec into clip
- If only conduction were active, area under beam would heat to **1400ºC** in 0.1 sec.

Centerstack



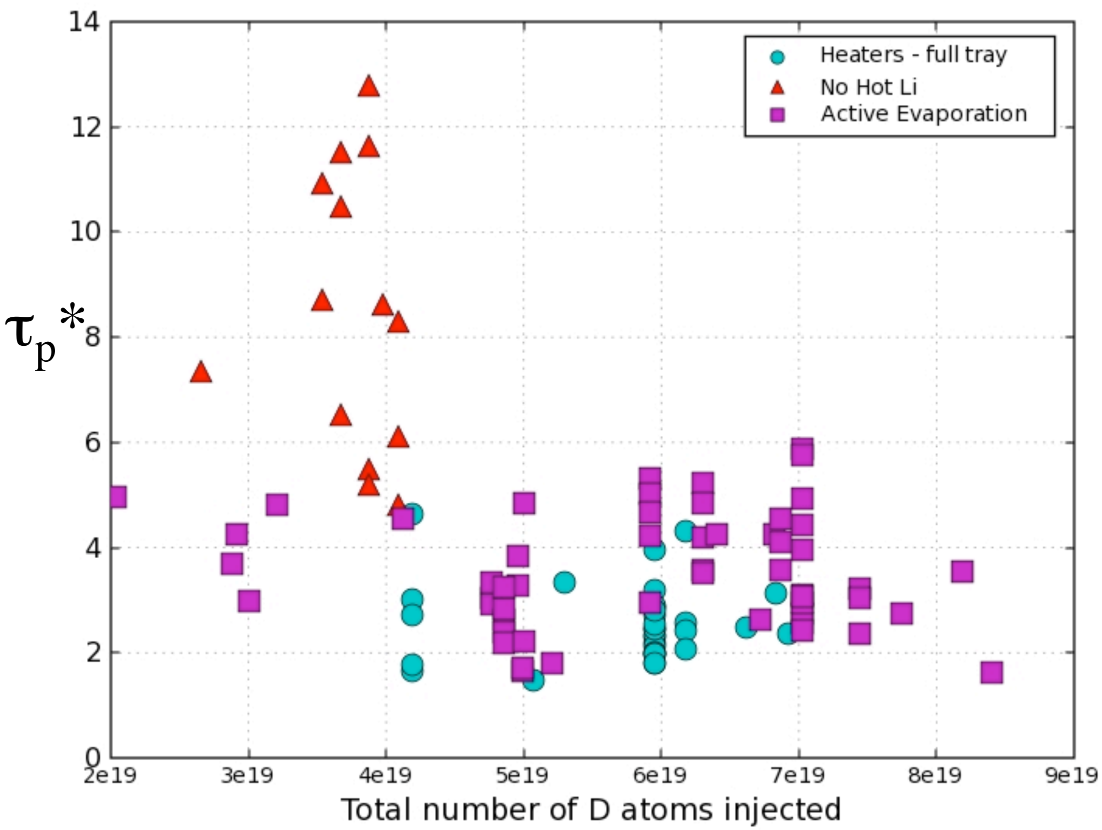
- Localized heat deposition (and/or beam current) induces lithium flows
  - –Marangoni effect; temperature-dependent surface tension

Entire tray heated, produced lithium wall coatings

Full wall coatings + partial liquid lithium tray produced very high particle pumping rates

CDX-U

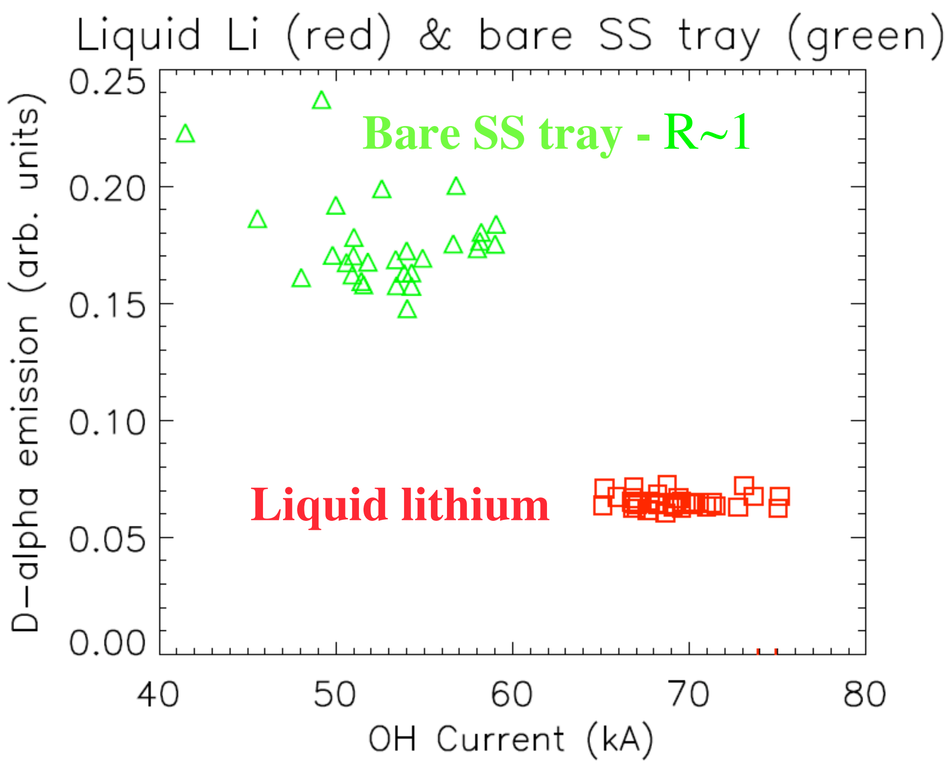
- Effective particle confinement time $\tau_p^* \equiv \tau_p/(1-R)$, R≡ recycling coefficient, reduced dramatically with liquid lithium limiters and wall coatings
  - τ_p^* too long to measure in the complete absence of lithium wall coatings



- Particle pumping rate in CDX-U is 1 - 2 × 10^{21} part/sec.
- Sufficient to pump a TFTR supershot
  - But the active wall area in CDX-U is only 0.4 m^2
  - *~Two orders of magnitude* less than the active wall area in TFTR during lithium wall conditioning.
- Liquid lithium also eliminated all traces of water
  - Oxygen vastly reduced
- Carbon, other impurities also reduced

Recycling coefficient estimated at ~0.3 for liquid lithium operation

- D_α emission at the centerstack
  - Primary plasma contact

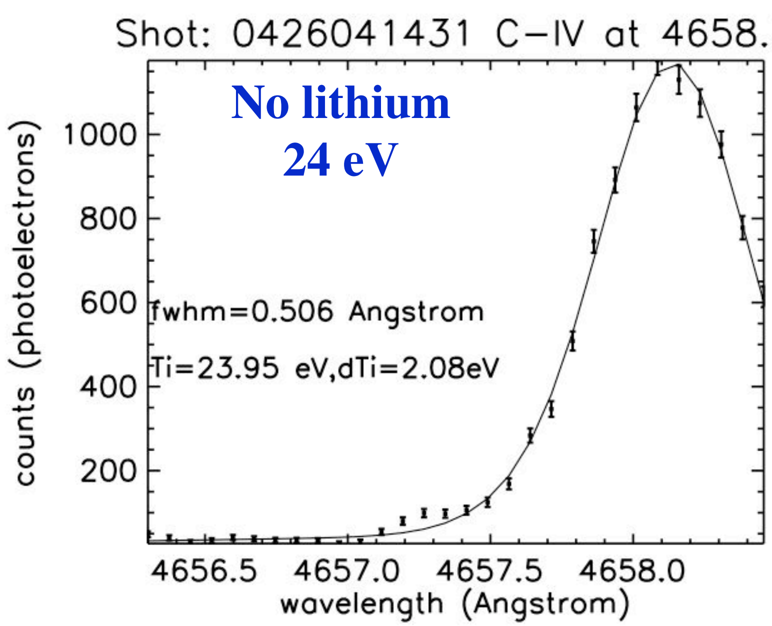


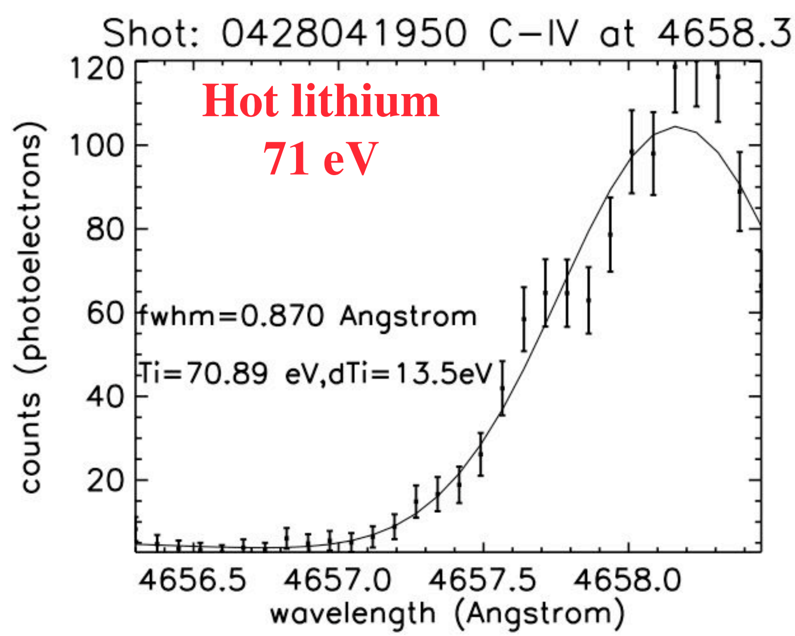
- ~3× reduction in D_α for liquid lithium operation
- Edge electron temperature:
  - ~28 eV with lithium
  - ~20 eV without
    - » ~17% correction in emission rate
- Edge electron density was ~1×10^{18} m^{-3} under both conditions
  - Bare tray: deuterium prefill only
  - Liquid lithium operation required 5-8 × increase in gas fueling
- Lithium reduces recycling coefficient from ~1 to ~0.3
  - Overestimate (background light)
- Lowest recycling coefficient ever measured for a magnetically confined plasma

Impurity ion temperature increases by 3× with lithium

CDX-U

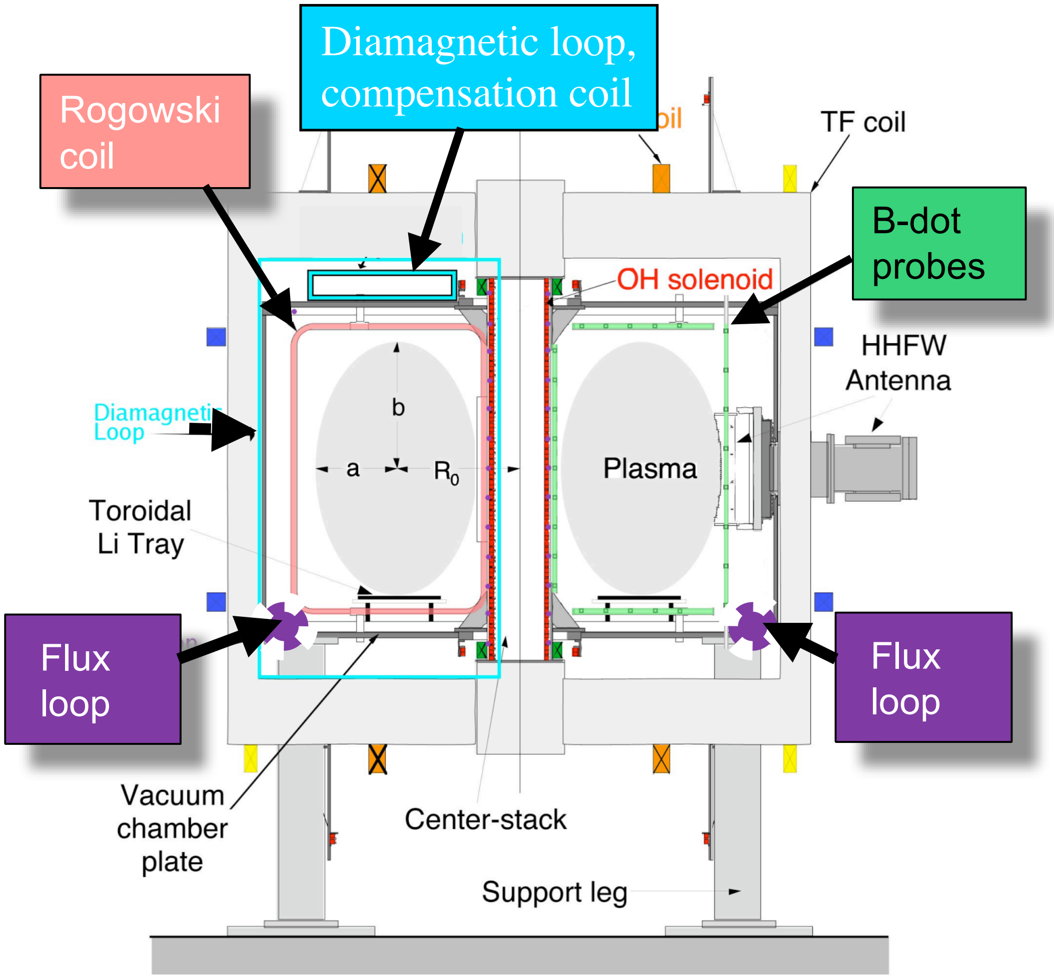
- Carbon impurity level (signal magnitude) drops by over an order of magnitude
- No profile information
- No Thomson scattering





New magnetic diagnostics permit reconstructions, measurement of τ_E

CDX-U LTX



- Magnetic probes, compensated diamagnetic loop added
- Equilibrium and Stability Code (ESC) modified to include vessel eddy currents
  - Response function approach
  - Calibrated with “step function” coil pulses
  - Compensation for nonaxisymmetric eddy currents

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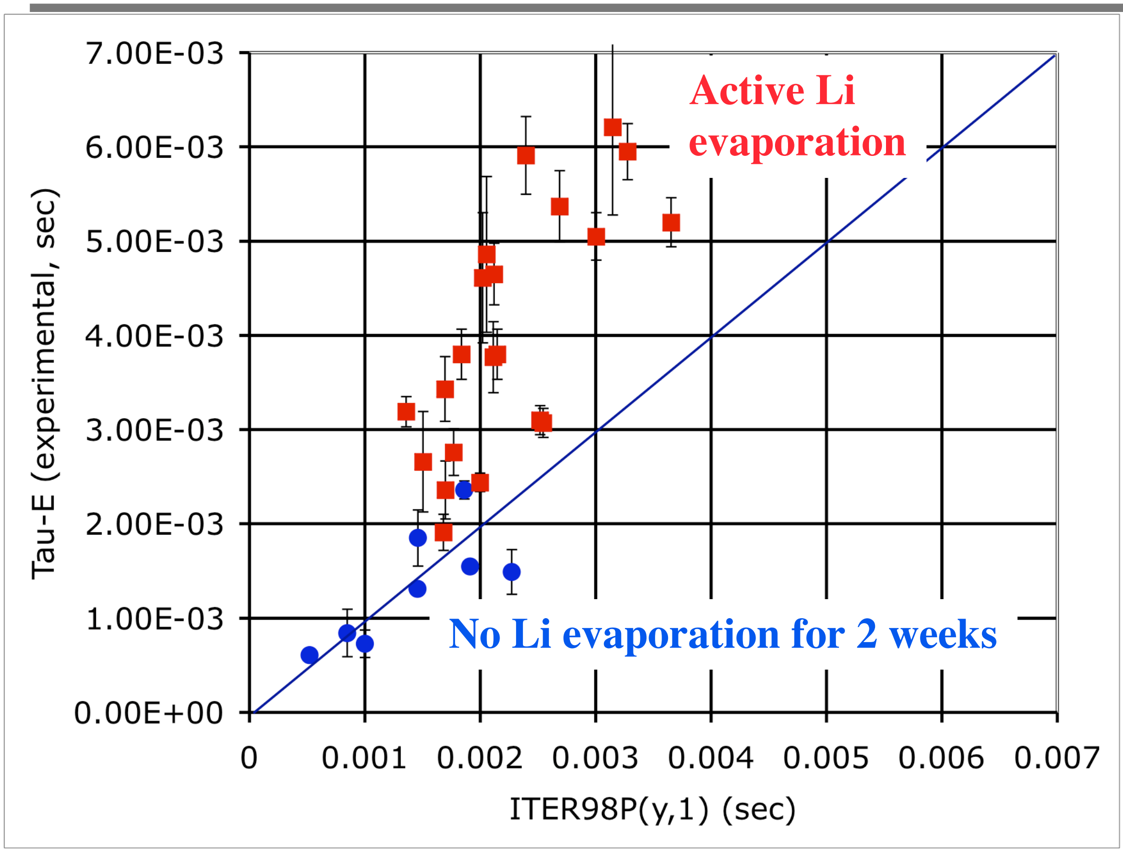
Measured confinement times exceed scalings

CDX-U

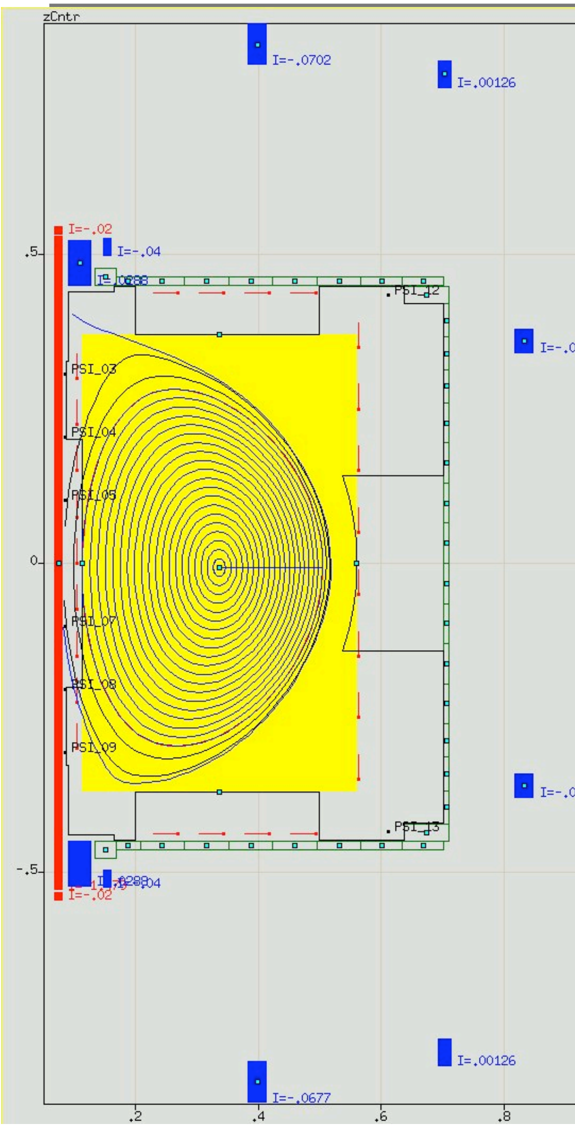


- $61\text{kA} < I_p < 78\text{kA}$
- 2.1 kG
- Identical loop voltage waveforms
- $0.5 < \overline{n}_e < 1 \times 10^{19}\ \text{m}^{-3}$

- ITER98P(y,1) included START data (slightly larger “small” ST)
- Confinement in CDX improved by 6× or more with lithium wall coatings, partial liquid lithium limiter
- Exceeds scaling by 2-3×
- Largest increase in ohmic tokamak confinement ever observed

Lithium discharges exhibit long confinement times, very low loop voltage

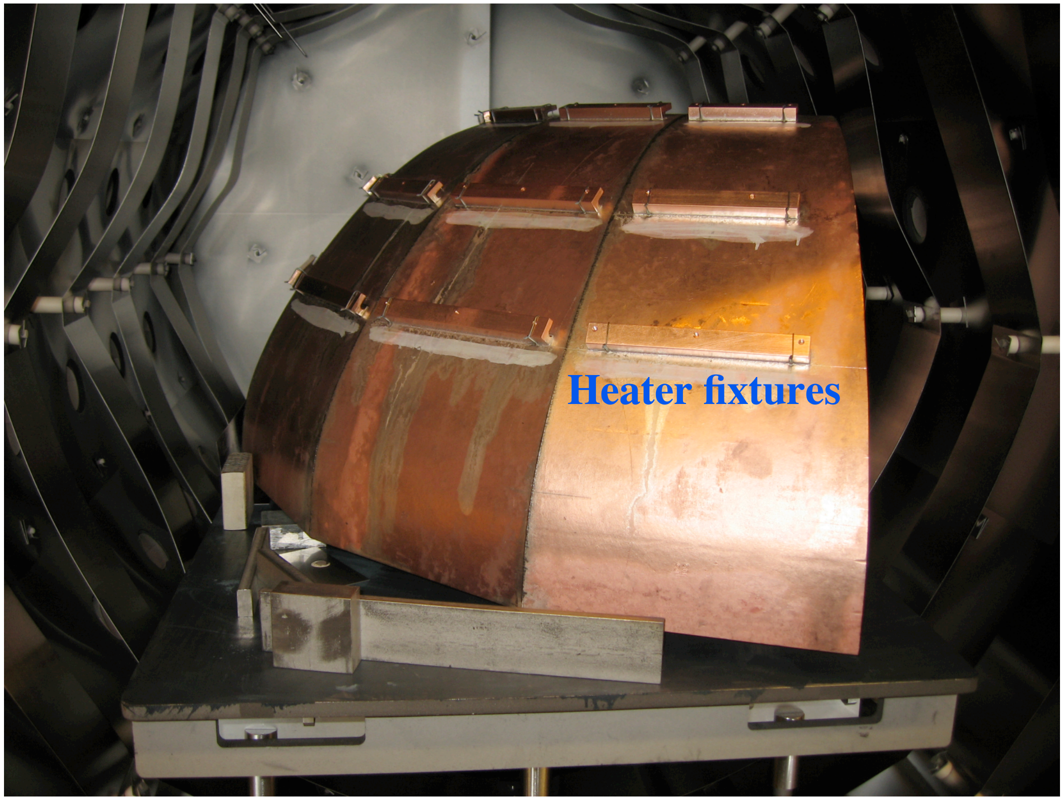
CDX-U

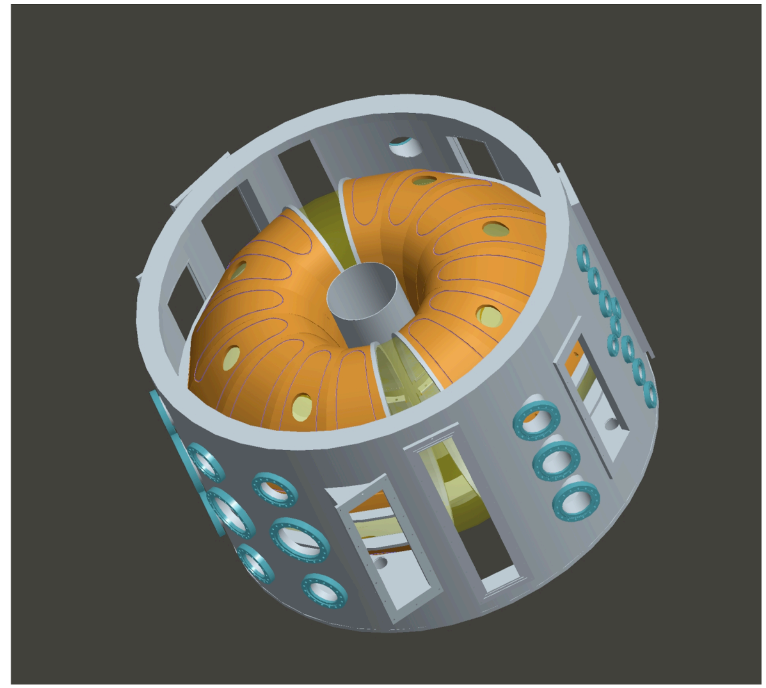


- Reconstruction of centerstack limited plasma from ESC
- Total coating of 6500 Å of lithium had been applied during preceding 90 min.
  - 900 Å applied 1 min. before discharge
- τ_E for this discharge exceeded 9 msec
  - Not shown in scaling plot
  - Exceeds ITER98 scaling by > 4×
  - Corresponding global χ_E is 5m^2/sec
- Surface voltage at current peak < 0.5V
  - 300 J stored energy
  - $L_i \sim 0.7$
  - Very low ohmic power input: 32 kW
  - Low ohmic power a future concern
    - » Lithium area 600 cm^2 for the discharges for which reconstructions are available
    - » Loop voltage was *lower* with a full (2000 cm^2) tray (2003, 2004)

LTX will have 5 m^2 wall of liquid lithium

CDX-U





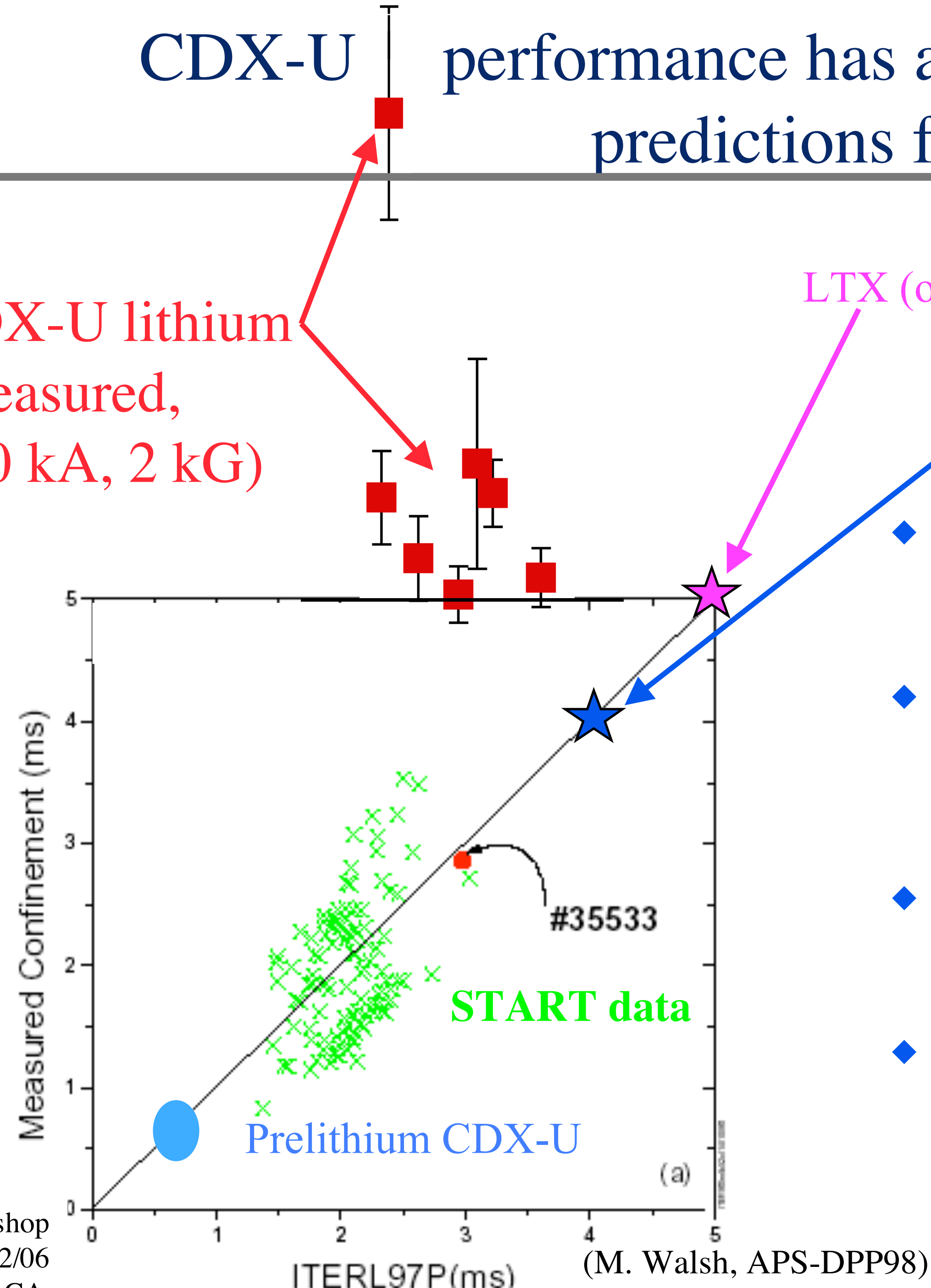
- Last shell segment coming out of the brazing furnace

- CAD view of shell in vessel
- First plasma in late CY2006

CDX-U performance has already greatly exceeded predictions for LTX

CDX-U

LTX



(M. Walsh, APS-DPP98)

- Projections from recent renewal submission (Spring 05)
  - L-mode scaling
- TSC, ASTRA projected confinement time for LTX at 3.8 kG, 250 kA was <3.1 msec (edge fueling)
- Observed confinement time for CDX-U at ~70 kA, 2.1 kG is already 2-3× higher
- Existing tokamak scalings are not good predictors for lithium tokamak performance

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Absorbing walls with core fueling may produce *very* long reactor confinement times

CDX-U

- Flat temperature profiles
  - No conduction losses
- Energy confinement time will be determined by *particle* confinement
- Particle confinement is *always* determined by the best confined species
- No temperature gradient drivers for ITG, other turbulence
  - No "profile consistency" for *density* profile
  - Particle transport in present machines may be driven by thermal instabilities
- Core fueled, nonrecycling lithium tokamak may have neoclassical confinement

$$D_{neo} \approx 0.016 \frac{n_{20}}{B_p^2 \sqrt{T_{i,10}}} \sqrt{\frac{a}{R}} \qquad (\mathrm{m^2/sec})$$

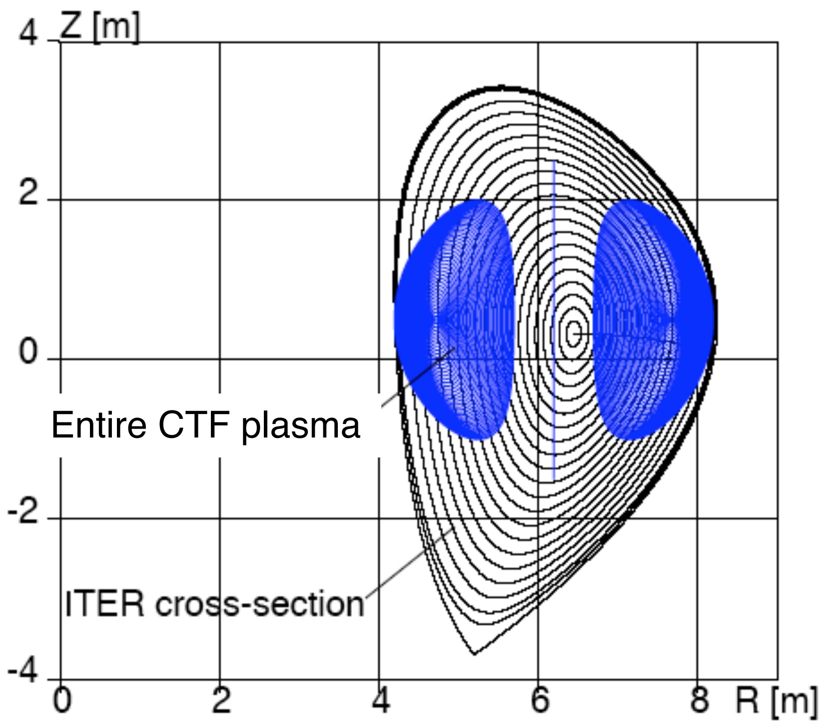
⇒ $\tau_E \sim \tau_p \sim \dfrac{a^2}{D_{neo}}$. $\tau_E > 10$ seconds for Component Test Facility with $a \sim 0.4$ m

⇒ CTF requires only 10 MW of NBI at 45 keV

- $T_e = T_i = 15$ keV
- Driven - no alpha confinement

Lithium tokamak leads to a simple, compact Component Test Facility for reactor R&D

CDX-U



CTF with TF, PF and blanket comparable in volume to present-day light water fission reactor pressure vessel (~100 m^3)

- PFC: 0.1-0.5 mm "creeping" lithium film in porous moly or tungsten surface
  - Required replacement rate: ~10 liter/hour (flow rate < 1 cm/sec) *for ITER*
- Small size = access for core fueling with low voltage NBI
- R_0=1.25m, a=0.75m, A=1.66, κ =2, 3T, 11 MA
- At 40% β, P_{fusion}=400 MW (=ITER)
  - Plasma volume =26 m^3
  - 3% of ITER
  - Manageable tritium requirements for reactor development

Summary

CDX-U

- In 2005 CDX-U simultaneously employed 600 cm^2 liquid lithium limiter + 1000 Å between-shots lithium wall coatings
- Simple, 3 mm deep liquid lithium pool was very effective at redistributing extremely high power density heat loads (~50 MW/m^2, 300 s.)
- Particle removal rates produced in CDX-U sufficient to pump a TFTR supershot
- Recycling coefficients of ~30% are the lowest ever achieved in a magnetically confined plasma
- 6-10 × enhancement in low recycling discharge confinement times over high recycling case
  - Largest increase in ohmic tokamak confinement ever observed
  - Empirical tokamak scalings appear irrelevant to lithium tokamaks
- CDX-U now being disassembled, converted to LTX
  - 25× increase in liquid lithium surface over best-case CDX-U
- Leads to a lithium walled CTF with a porous-metal lithium-filled PFC
  - Porous metal walls with slow flow are presently under development via Phase I and Phase II SBIRs